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A New Weak Area Identification Method in Power System Based on Voltage Stability

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Abstract— Identification of voltage stability weak area in power system plays an important role in preventing the occurrence of voltage collapse. A fast and accurate identification method helps power system operators to apply voltage stability control action on the weak area and thus avoids voltage collapse. This paper presents a new technique for weak area identification in a power system based on voltage stability named as Weak Area Indicator (WAI). WAI is derived from a newly developed voltage stability index, Voltage Stability Condition Indicator (VSCI). For verification purpose, the proposed WAI was tested with the existing method in the literature that used voltage stability variation method to detect weak area. Test results show that the proposed WAI is able to cluster weak areas correctly. All methods were tested on IEEE 30-bus and IEEE 118-bus test system.

Index Terms—Voltage Collapse; Voltage Stability; Voltage Stability Index; Weak Area.

I. INTRODUCTION

Voltage collapse is the result of a series of voltage instability which can eventually lead to a power blackout [1]. It has been agreed that the voltage instability problems start locally at the weakest bus, spread to the neighboring buses, and progressively extend to the overall system [2, 3]. By considering a large power system network that can be grouped into a smaller sub network, weak area can be identified.

The weak area contains the weakest bus and the load buses that are strongly connected to it where these buses have similar voltage behavior patterns [2, 3]. These buses are prone to voltage instability at a certain operating condition of the power system. By having such information early, the system operators will be able to focus and take some preventive actions more efficiently to the area. These preventive actions include load shedding, reactive power compensation, and active or reactive power control [4]. As a result, the stability of the power system network can be sustained.

In additional, the computational speed of many applications on the power system is proportional to the size of the power system network. For that reason, identification of weak area may also reduce the computation burden since amounts of information that must be analysed in short time intervals have been reduced.

Several methods for weak area identification have been reported in the literature. In reference [3], weak area

clustering is referred to as a network partitioning. In this reference, a network partitioning is proposed based on the voltage variations at the critical bus in relation to a load variation at the other load buses. The loads variation considered are both active and reactive power load. The weakest bus is first identified by using the determinant of the inverse Jacobian matrix of the load flow. The network partitioning is then conducted by using the determinant, Gil of the inverse matrix M. Matrix M is the reduced load flow Jacobian matrix of the critical bus that relates the phase angle and voltage level variation at the critical bus with a load variation at another load bus. If the value of the determinant, Gil is greater than a specified value k, bus i is considered to be strongly connected to the critical bus and hence belongs to the weak area. Different operating points may lead to a different network partitioning since each operating points may be associated to different value of k.

T. K. Abdul Rahman had proposed another weak area clustering method using the variation method [5]. The critical area is identified by using voltage stability variation where two sensitive indicators are created from the developed voltage stability index, L. The two sensitive indicators are the variation of the Index L at the critical bus i with respect to the active and reactive load variations at another bus j, $\partial Li/\partial Pj$ and $\partial Li/\partial Qj$. The greater value between the two indicators is chosen to be normalised by using their respective change in the index L over change in active or reactive load at the critical bus, $\partial Li/\partial Pi$ and $\partial Li/\partial Qi$. The normalised values are then ranked in descending order. The load buses with the sensitive index is larger than the cut-off value are clustered into the critical area. The different between this method and the previous method is that the voltage stability index variation is used instead of the voltage variation. The cut-off values for both methods are determined by the coherency in the change in voltage magnitude and phase angle of the load buses between the base case and the loaded condition. There are only two areas, stable and unstable areas.

Weak area clusters can also be formed by using line stability index. Musirin had developed a line stability index called FVSI [6], and introduced a method for weak area clustering identification [7]. In this study, weak area clustering is developed based on the sensitive lines deduced from the voltage stability analysis that integrates the results from two separate methods. The first method is from the elimination of the weak lines. An automatic line outage

contingency ranking is performed in order to identify the weak lines. FVSI values for each line outage are calculated in which the values are ranked in descending order. From the ranking, line clusters that contain weak lines are identified. The second method identifies the weak lines by applying voltage stability analysis by using FVSI. The severity of the lines is determined by calculating FVSI value. A cut-off value of FVSI is set as a threshold value to form the sensitive line clusters. The resemblances between the clusters developed by sensitive lines and critical line outages are realized in order to form resultant clusters which are the weak area clusters. This technique also has only two weak area clusters, stable and non-stable area.

In the literature, formation of voltage control area (VCA) is another method that produces few weak area groups for large-scale power systems. VCA presented in [8] uses the full Newton Raphson load flow Jacobian sensitivities along with voltage variations under several different contingencies. The proposed method studies the effect of P-V and Q- δ coupling and changes in network topology. The elimination of weaker off-diagonal terms of the normalised Jacobian sub matrices is employed for weak areas clustering. To determine VCAs that valid for both the system intact and contingency cases, the formed bus clusters are modified by observing the voltage variations of the load buses due to occurrence of the contingencies. The coherency in the voltage variation is another indication exploited in this research to reform a new weak area cluster. In order to employ fast voltage stability assessment effectively, each of the voltage control areas developed by the proposed method is reduced to equivalent nodes by a network reduction technique, REI reduction technique. In reference [9], the author employs the electrical distance between nodes and the decision tree algorithm to obtain the VCA and the required reserves from a given system condition. Meanwhile in reference [10], clustering algorithm is used to determine the VCA.

On the other hand, Wan et al. has presented a neural network (ANN) based method for voltage weak area identification [11]. In this study, the application of Kohonen's self-organizing neural network is introduced. From the Kohonen network, different buses can be efficiently grouped to the corresponding positions on the output neuron grid under different operating conditions. The unsupervised neural network is able to classify the weak region which consists of several buses for different operating condition. The accuracy of the feature extraction of the Kohonen network is ensured by employing sufficient information of voltage stability as the input data vector. The input data used in this study are the load and the ratio between the voltage difference of a load bus and the sum of the voltage difference for all load buses under a specific loading condition. A large number of operating conditions related to voltage stability are considered. The operating conditions cover variety range of the voltage stability from stable to unstable state. In order to analyse the properties of the developed clusters in the Kohonen output map, singular value decomposition method is utilized. The weakest operating condition is classified at the right edge of the output and its nearby neurons. The drawback of this method is that it is not independent since the analysis from the singular value decomposition and power flow method are required to describe the properties of the clusters. In reference [12], ANN is used to predict the voltage stability

index for weak area identification.

Besides that, there are also several researches on weak area identification in dynamic analysis [13-16]. In reference [13], weak area is identified based on the exposure to voltage sags. The approach takes into account the stochastic nature of power system operation, including load variation, uncertainty of fault clearing time by protection relays, fault rates of network components, and the variation/uncertainty in equipment sensitivity to voltage sags. A new index with respect to voltage sags (bus performance index) is developed to represent the overall bus performance with respect to voltage sags. The weak area is then identified based on the developed index.

Despite of the importance of identifying the weak area in a system, there are only few methods proposed in the literature in which most of them are based on conventional and complicated approaches. Therefore, a new method on identification of weak area named as Weak Area Indicator (WAI) is developed in this research. WAI is derived from a newly developed voltage stability index termed as Voltage Stability Condition Indicator (VSCI). The originality of this method compared to the methods that have been discussed in the literature is that the formulation of WAI is based on the acknowledgement of a critical bus, a bus that may lead the system to voltage collapse. In contrast to other existing methods, the application of WAI takes into account the impact of load increase on the critical bus. The variation in voltage and angle are used as the cut off value to determine the weak area cluster boundary.

II. VOLTAGE STABILITY INDEX

A newly developed voltage stability index named as Voltage Stability Condition Indicator (VSCI) is used to determine the voltage stability state of a system. VSCI is a new bus voltage stability index. It was derived from the current equation in a complex form of a simple 2-bus Thevenin equivalent system.

Looking at the load bus concerned, the equation of current, I in complex form can be written as,

$$\bar{I} = \frac{E_{Th} \angle \phi - V_L \angle \delta}{Z_{Th} \angle \beta} \quad (1)$$

where:

$E_{Th} \angle \phi$ = Thevenin voltage or the open circuit voltage at the bus concerned,

$Z_{Th} \angle \beta$ = Thevenin impedance or the total equivalent impedance across the bus,

$Z_L \angle \theta$ = equivalent impedance of the load connected to the bus,

$V_L \angle \delta$ = voltage at that bus concerned

and ϕ, β, θ , and δ are their corresponding phase angles.

By using real and imaginary terms, a quadratic equation as shown below is then formulated:

$$V_L^4 + (2Z_{Th}(P \cos \beta + Q \sin \beta) - E_{Th}^2)V_L^2 + Z_{Th}^2(P^2 + Q^2) \quad (2)$$

Equation (2) above will only have real root if the discriminant is greater or equal to 0. Therefore, it can be simplified to

$$VSCI = \frac{4Z_{Th}^2(P^2 + Q^2)}{(2Z_{Th} \cos \beta + Q \sin \beta - E_{Th}^2)^2} \leq 1 \quad (3)$$

where P and Q are the active and reactive load.

III. PROPOSED WEAK AREA IDENTIFICATION METHOD

WAI is formulated based on the concept of voltage stability index margin of the most critical load bus between a specified initial point and identified collapse point. This method studies the effect of the voltage stability at the critical bus when there is a load increase at other load buses. VSCI is used in WAI as the voltage stability condition indicator since it provides a direct relationship between voltage stability and the active and reactive power load and hence is able to deliver a reliable and fast indication of the proximity to voltage collapse. Similar approach was implemented as in reference [17], in which PTSI was used as the indicator of maximum permissible load of a load bus.

WAI is derived based on the effect of load increment at other load buses to the voltage stability condition at the most critical bus in a system. Load buses that give significant changes to the voltage stability condition of the most critical bus are considered to be in the weak area because voltage collapse might occur as a result of reactive power load increase at these load buses. In other words, load buses which resulted in high WAI value are considered to be closely related to the critical bus and included in the same weakest area. Besides that, it has also been confirmed that buses in a cluster behave in a coherent manner [2-3, 5] where the changes in voltage and angle at these buses are about the same for any control action or contingency [2, 3, 5]. Therefore, the changes in voltage and angle are used as a coherency indicator or the cut off value to determine the weak area cluster boundary. All generator buses connected to these buses are considered to belong to the clustered weak area.

To determine the weak area, a voltage stability analysis in a power system by using WAI is conducted. From the analysis, weak boundaries subjected to increase in reactive power loading are identified. In this method, WAI is used to indicate the relation of other load buses and the critical bus in the system as buses that are strongly connected are grouped into one cluster. The algorithm of the proposed method is outlined as follows:

Step 1: Obtain the value of Thevenin voltage magnitude and angle for each load bus by running load flow with the load connected at the bus concerned removed subjected to a predetermined condition.

Step 2: Run load flow to compute the voltage profile and power flow in the system.

Step 3: Calculate VSCI value for each load bus. The load bus with the highest value of VSCI is identified as the most critical bus in the system.

Step 4: Increase load at every load buses other than the most critical bus identified in Step 3, until the system reaches its collapse point. This step is important in order to investigate the relationship between the other load buses and the most critical bus.

Step 5: Normalise WAI values for all load buses.

Step 6: Rank the normalised WAI values in descending order.

Step 7: Cluster the weak area by highlighting the bus system configuration graphically. Load buses which are included in the weak areas are identified based on the coherency in the change of voltage and phase angle of the load buses between the initial case and the final case. More than one cluster of weak area can be formed depending on the interconnection between these buses.

IV. VOLTAGE STABILITY VARIATION METHOD FOR WEAK AREA IDENTIFICATION

For validation purpose, the performance of the proposed WAI is compared with the performance of weak area determination technique using Voltage Stability Variation Method. By considering the L-Index [18], two indicators to identify weak area were developed. The formulation of L-Index is as follow:

$$L = \frac{4}{V_i^2} (V_i V_{i+1} \cos(\theta_i - \theta_{i+1}) - V_{i+1}^2 \cos(\theta_i - \theta_{i+1}))^2 \quad (6)$$

The changes in L at the critical bus, i with respect to changes in active and reactive power demand at load bus j are given by the partial derivatives as in the following equations:

$$\frac{\partial L_i}{\partial P_j} = \frac{\partial \theta_i}{\partial P_j} \times \frac{\partial L_i}{\partial \theta_j} + \frac{\partial V_i}{\partial P_j} \times \frac{\partial L_i}{\partial V_j} \quad (7)$$

$$\frac{\partial L_i}{\partial Q_j} = \frac{\partial \theta_i}{\partial Q_j} \times \frac{\partial L_i}{\partial \theta_j} + \frac{\partial V_i}{\partial Q_j} \times \frac{\partial L_i}{\partial V_j} \quad (8)$$

Rephrasing equations (7) and (8) into matrix form,

$$\begin{bmatrix} \frac{\partial L_i}{\partial P_j} \\ \frac{\partial L_i}{\partial Q_j} \end{bmatrix} = \begin{bmatrix} \frac{\partial \theta_i}{\partial P_j} & \frac{\partial V_i}{\partial P_j} \\ \frac{\partial \theta_i}{\partial Q_j} & \frac{\partial V_i}{\partial Q_j} \end{bmatrix} \begin{bmatrix} \frac{\partial L_i}{\partial \theta_j} \\ \frac{\partial L_i}{\partial V_j} \end{bmatrix} \quad (9)$$

where

$$\begin{bmatrix} \frac{\partial \theta_i}{\partial P_j} & \frac{\partial V_i}{\partial P_j} \\ \frac{\partial \theta_i}{\partial Q_j} & \frac{\partial V_i}{\partial Q_j} \end{bmatrix} \text{ is the inverse Jacobian matrix} \quad (10)$$

By differentiating equation (6) with respect to θ and V ,

$$\frac{\partial L_i}{\partial \theta_j} = \frac{4V_i \sin(\theta_0 - \theta_i)(2V_i \cos(\theta_0 - \theta_i) - V_0)}{V_0^2} \quad (11)$$

$$\frac{\partial L_i}{\partial V_j} = \frac{4(V_0 \cos(\theta_0 - \theta_i) - (2V_i \cos^2(\theta_0 - \theta_i)))}{V_0^2} \quad (12)$$

Equations (11) and (12) are the two indicators developed to identify the weak area in this method. Both indicators are calculated for every load buses and the greater value among the two is chosen for the ranking. The normalised value of the chosen indicator is then ranked in descending order.

The normalised value is obtained by dividing $\frac{\partial L_i}{\partial P_j}$ and

$\frac{\partial L_i}{\partial Q_j}$ by $\frac{\partial L_i}{\partial P_i}$ and $\frac{\partial L_i}{\partial Q_i}$ respectively where:

$\frac{\partial L_i}{\partial P_i}$ is the change in voltage stability with respect to change in active power demand at the critical bus i .
 $\frac{\partial L_i}{\partial Q_i}$ is the change in voltage stability with respect to change in reactive power demand at the critical bus i .

V. RESULTS AND DISCUSSIONS

MATLAB programming language was used to develop programmes for the simulations. In this paper, the performances of all methods were tested on IEEE 30 bus and IEEE 118 bus test system. The results from both methods were highlighted graphically on the bus system configuration.

A. Weak Area Identification of IEEE 30 Bus Test System
IEEE 30 bus test system has 1 swing bus, 5 generator buses and 24 load buses with 41 interconnected lines. Bus 30 was identified as the most critical bus in the system by using the method developed in [19]. Table 1 tabulates the results of the performance of WAI while Table 2 tabulates the results by voltage stability variation method. Based on the coherency in angle and voltage variation explained in Section III, the cut off value chosen for Table I is 0.248 while for Table II is 0.759. Figure 1 and Figure 2 illustrates weak area cluster highlighted on the bus system configuration of IEEE 30 bus system for both methods. Based on the tables and figures, both methods show similar results with bus 30, 29, 27, 26 and 25 are grouped in a cluster to form the weak area.

Table 1
The performance of WAI of IEEE 30 bus system

BUS	WAI	Angle Change (rad.)	Voltage Change (p.u.)
30	1.000	-	-
29	0.998	2.452	0.080
27	0.351	0.519	0.019
26	0.259	0.391	0.014
25	0.248	0.368	0.013
24	0.095	0.154	0.005
23	0.055	0.098	0.003
22	0.045	0.087	0.003
21	0.041	0.082	0.002
28	0.035	0.057	0.002
10	0.029	0.064	0.002
20	0.028	0.063	0.002
19	0.028	0.063	0.002
18	0.027	0.061	0.002
17	0.026	0.060	0.002
15	0.026	0.057	0.002
16	0.018	0.048	0.001
14	0.018	0.048	0.001
9	0.013	0.036	0.001
12	0.010	0.035	0.001
6	0.006	0.021	0.001
4	0.003	0.020	0.001
3	0.001	0.019	0.000
7	0.000	0.012	0.000

Table 2
The performance of voltage stability variation method of IEEE 30 bus system

BUS	dldpdq	Angle Change (rad.)	Voltage Change (p.u.)
30	1.000	2.452	0.080
27	1.000	0.151	0.011
29	0.909	1.174	0.066
25	0.829	0.007	0.009
26	0.759	0.256	0.016
24	0.377	0.033	0.004
23	0.260	0.057	0.004
22	0.243	0.013	0.002
21	0.191	0.012	0.002
20	0.166	0.046	0.003
10	0.164	0.000	0.002
18	0.155	0.058	0.004
28	0.152	0.008	0.001
19	0.146	0.054	0.004
17	0.143	0.017	0.002
15	0.136	0.024	0.002
16	0.115	0.034	0.003
14	0.109	0.069	0.003
9	0.083	0.001	0.001
12	0.067	0.001	0.001
3	0.041	0.010	0.001
6	0.040	0.002	0.000
4	0.038	0.005	0.001
7	0.000	0.013	0.001

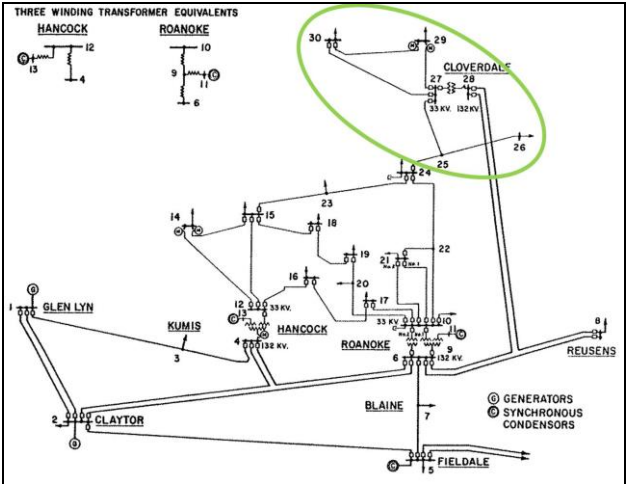


Figure 1: Weak area cluster of IEEE 30 bus test system using WAI.

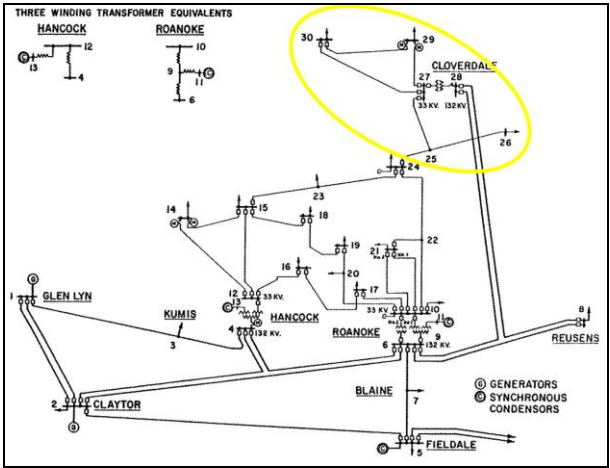


Figure 2: Weak area cluster of IEEE 30 bus test system using voltage stability variation method.

B. Weak Area Identification of IEEE 118 Bus Test System

To expand the breadth of the study, another test is conducted on IEEE 118 bus test system. This system has 54 generator buses and 99 load buses with 186 interconnected lines. Bus 44 was identified as the weakest bus in the system subjected to a predetermined condition. Table 3 and 4 show the weak area identification performance of WAI and Voltage Stability Variation Method respectively. In Table 3, the cut off value of 0.604 is chosen since it is observed that there is coherency in the variations of voltage magnitudes and angles at the critical bus due to load changes at these buses and hence the weak area is formed by buses 44, 45 and 43. Likewise, from Table IV, bus 44, 45 and 43 are identified to form the weak area where the cut off value of dldpdq is chosen to be 0.971. The weak area formed highlighted on the bus system configuration of IEEE 118 bus test system for both methods are illustrated in Figure 2. Based on the tables and figures, once again WAI gives the similar result with Voltage Stability Variation Method with load bus 44, bus 45 and bus 43 are identified as the weak load buses, hence are grouped as the weak area cluster.

Table 3
The performance of WAI of IEEE 118 bus system

BUS	WAI	Angle Change (rad)	Voltage Change (p.u)
44	1.000	1.498	0.044
45	0.712	1.937	0.054
43	0.604	1.498	0.044
47	0.006	0.052	0.000
38	0.005	0.034	0.000
21	0.003	0.026	0.000
22	0.003	0.024	0.000
20	0.002	0.018	0.000
33	0.002	0.016	0.000
37	0.002	0.015	0.000
117	0.002	0.015	0.000
30	0.002	0.012	0.000
13	0.002	0.012	0.000
39	0.002	0.012	0.000
52	0.002	0.014	0.000
48	0.001	0.011	0.000
53	0.001	0.011	0.000
51	0.001	0.009	0.000
16	0.001	0.007	0.000
58	0.001	0.008	0.000
41	0.001	0.006	0.000
28	0.001	0.006	0.000
81	0.001	0.006	0.000
2	0.001	0.005	0.000
68	0.001	0.005	0.000
57	0.001	0.005	0.000
14	0.001	0.004	0.000
35	0.001	0.004	0.000
29	0.001	0.004	0.000
50	0.001	0.004	0.000
11	0.000	0.004	0.000
115	0.000	0.003	0.000
3	0.000	0.003	0.000
114	0.000	0.003	0.000
75	0.000	0.003	0.000
23	0.000	0.003	0.000
17	0.000	0.002	0.000
118	0.000	0.002	0.000
95	0.000	0.002	0.000
67	0.000	0.002	0.000
63	0.000	0.002	0.000
101	0.000	0.002	0.000
93	0.000	0.002	0.000

64	0.000	0.002	0.000
84	0.000	0.002	0.000
106	0.000	0.001	0.000
94	0.000	0.001	0.000
109	0.000	0.001	0.000
71	0.000	0.001	0.000
108	0.000	0.001	0.000
7	0.000	0.001	0.000
102	0.000	0.001	0.000
98	0.000	0.001	0.000
86	0.000	0.001	0.000
97	0.000	0.001	0.000
88	0.000	0.001	0.000
60	0.000	0.001	0.000
96	0.000	0.001	0.000
83	0.000	0.001	0.000
82	0.000	0.000	0.000
79	0.000	0.000	0.000
9	0.000	0.000	0.000
78	0.000	0.000	0.000
5	0.000	0.000	0.000

Table 4
The performance of voltage stability variation method of IEEE 118 bus system

BUS	dldpdq	Angle Change (rad)	Voltage Change (p.u)
44	1	25.003	0.314
43	1	13.644	0.143
45	0.971	14.217	0.181
50	0.001	6.033	0.007
48	0.001	6.93	0.015
51	0.001	5.798	0.004
52	0.001	5.74	0.003
57	0.001	5.664	0.003
53	0	5.551	0.001
58	0	5.62	0.002
47	0	6.36	0.019
67	0	4.432	0
60	0	4.175	0
63	0	4.118	0.001
64	0	3.929	0.001
38	0	6.043	0.009
23	-0.001	4.744	0.001
22	-0.001	5.167	0.005
30	-0.001	5.878	0.003
21	-0.001	5.45	0.007
114	-0.001	5.329	0
9	-0.001	5.933	0
5	-0.001	5.957	0
17	-0.001	5.939	0.001
115	-0.001	5.33	0
28	-0.001	5.408	0
20	-0.001	5.697	0.009
41	-0.001	7.093	0
29	-0.001	5.491	0
37	-0.001	7.162	0.01
14	-0.001	6.026	0
7	-0.001	5.975	0
2	-0.001	5.979	0
16	-0.001	5.969	0
33	-0.001	6.634	0.005
117	-0.002	5.983	0
13	-0.002	6.019	0
39	-0.002	7.175	0.004
3	-0.002	5.971	0
11	-0.002	5.98	0
35	-0.002	7.224	0.018
109	0	1.441	0
68	0	2.234	0
81	0	1.962	0
102	0	1.419	0
93	0	1.418	0
108	0	1.441	0

97	0	1.46	0
84	0	1.368	0
94	0	1.422	0
83	0	1.349	0
96	0	1.411	0
95	0	1.417	0
101	0	1.43	0
98	0	1.484	0
78	0	1.23	0
79	0	1.304	0
82	0	1.337	0
86	0	1.377	0
88	0	1.392	0
106	0	1.441	0
118	0	0.95	0
75	0	0.89	0

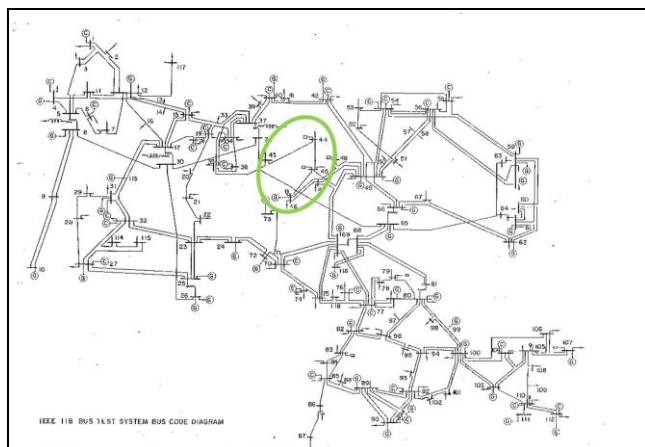


Figure 3: Weak area cluster of IEEE 118 bus test system using WAI.

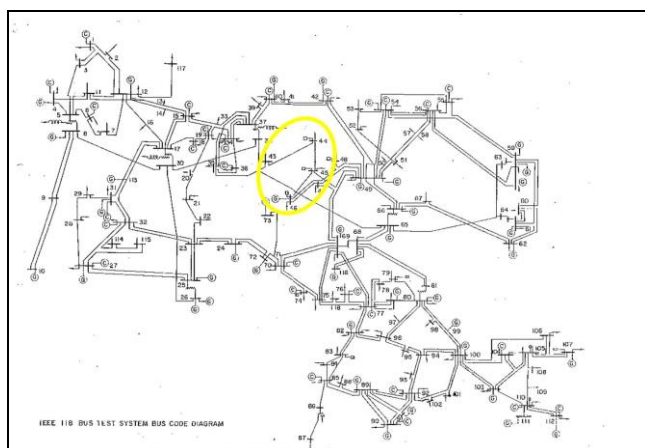


Figure 4: Weak area cluster of IEEE 118 bus test system using voltage stability variation method.

VI. CONCLUSION

In this paper, a new method to detect weak areas in a power system based on voltage stability named as Weak Area Indicator (WAI) is presented. The proposed method uses a newly developed voltage stability index, VSCI to determine the voltage stability of the system. The formulation of WAI is based on the acknowledgement of the weakest bus, a bus that may lead the system to voltage collapse. In contrast to other existing methods, the application of WAI takes into account the impact of load increase at other load buses on the critical bus. The coherency of variation in voltage and angle are used as the cut off value to determine the weak area cluster boundary.

For validation purpose, the proposed WAI performance was compared with the existing weak area identification method known as Voltage Stability Variation method. The tested results have shown that the proposed WAI is able to cluster weak areas correctly. The weak area cluster is observed to group the buses which are directly and closely connected to the most critical bus. WAI is simple and straight forward, yet able to identify weak area correctly when compared to a more complicated method. Therefore, WAI can be explored further in online application for a fast weak area identification.

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